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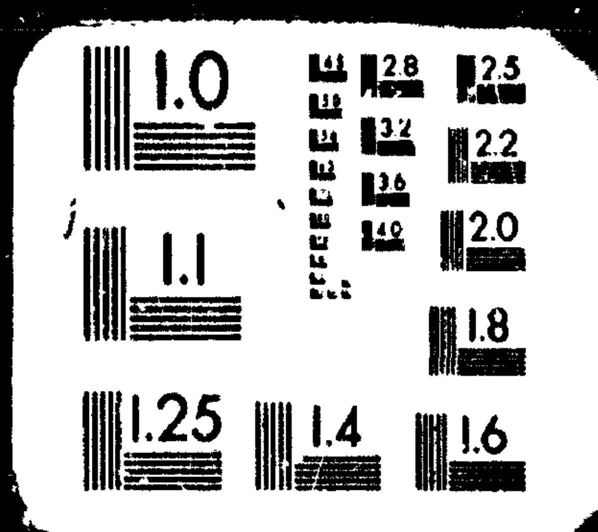

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Special Investigation Report - Tank Car Structural Integrity After Derailment

(U.S.) National Transportation Safety Board
Washington, DC

16 Oct 80

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NATIONAL TRANSPORTATION SAFETY BOARD

WASHINGTON, D.C. 20594

SPECIAL INVESTIGATION REPORT

TANK CAR STRUCTURAL INTEGRITY AFTER DERAILMENT

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16. Abstract

Since 1968, the Safety Board has investigated many serious accidents involving release of hazardous materials from tank cars which were either breached or ruptured following derailments. As a result of these investigations, the Safety Board recommended that Federal authorities take remedial action to reduce the likelihood of tank cars releasing their contents in the derailment environment.

During its investigation of a railroad derailment near Inwood, Indiana, on November 8, 1979, the Safety Board noted unresolved questions about the dangers posed in handling severely damaged tank cars containing liquefied flammable gases at the accident site. Because of this continuing problem, the Safety Board initiated this special investigation to identify the hazards caused by the actual reduction of the ability of damaged cars to contain their lading; to determine the ability of experts to estimate this reduced capability; and to examine the feasibility of developing practical guidelines to help determine how damaged hazardous materials tank cars should be handled.

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ABSTRACT (Continued)

Cooperating with the Safety Board as parties to this special investigation were the Federal Railroad Administration, the Association of American Railroads, the Compressed Gas Association, Hulcher Emergency Services, and the General American Transportation Corporation. Members of the investigative group included experts in fracture mechanics, tank car design, compressed gas shipments, and hazardous materials.

The Safety Board made recommendations to the Research and Special Programs Administration of the Department of Transportation, the Federal Railroad Administration, and the Association of American Railroads concerning safeguarding of wreck-clearing crews at derailment sites in which hazardous materials are involved.

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NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C. 20594

SPECIAL INVESTIGATION REPORT

Adopted: October 16, 1980

TANK CAR STRUCTURAL INTEGRITY AFTER DERAILMENT

INTRODUCTION

Since 1968, the Safety Board has investigated many serious accidents involving release of hazardous materials from tank cars which were either breached or ruptured following derailments. As a result of these investigations, the Safety Board recommended that Federal authorities take remedial action to reduce the likelihood of tank cars releasing their contents in the derailment environment. 1/

During its investigation of a railroad derailment near Inwood, Indiana, on November 8, 1979, the Safety Board noted unresolved questions about the dangers posed in handling severely damaged tank cars containing liquefied flammable gases at the accident site. Because of this continuing problem, the Safety Board initiated this special investigation to identify the hazards caused by the actual reduction of the ability of damaged cars to contain their lading; to determine the ability of experts to estimate this reduced capability; and to examine the feasibility of developing practical guidelines to help determine how damaged hazardous materials tank cars should be handled. The Safety Board is also investigating the accident to determine the probable cause, and a Brief of Accident will be issued when that investigation is completed.

Safety Board recommendations have resulted in the installation of additional shielding and the installation of couplers which resist vertical separation. These safety improvements have been instrumental in reducing tank car head punctures. Insulation and thermal coatings have also been applied at the Board's insistance to lessen the possibility of the rupture of tank cars in a fire. Some of these safeguards have effectively reduced the probability of tank car breach and tank car rupture during the derailment process. 2/

1/ Safety Effectiveness Evaluation: "Analysis of Proceedings of the National Transportation Safety Board Into Derailments and Hazardous Materials, April 4-6, 1978" (NTSB-SEE-78-2); "Safety Report on the Progress of Safety Modification of Railroad Tank Cars Carrying Hazardous Materials" (NTSB-SR-79-2)
2/ Special Investigation Report: "The Accident Performance of Tank Car Safeguards" (NTSB-HZM-80-1).

These safety improvements have reduced hazardous material tank car breaches and ruptures during derailments. However, they do not eliminate risks of ruptures during wreck-clearing operations. The Safety Board is aware of 24 fatalities and 118 injuries in such accidents. A 1959 accident at Monroe, Louisiana, caused 8 fatalities and injured 75 persons. 3/ The continuing dangers inherent in these operations were clearly demonstrated again during the clearing of the wreckage following the February 22, 1978, derailment of 23 cars in a Louisville and Nashville freight train in Waverly, Tennessee. 4/ Two days after the derailment, a tank car containing liquefied petroleum gas ruptured and released the product. The ensuing fire claimed the lives of 16 persons and injured 43. This car had suffered mechanical damage in the derailment and had been moved in preparation for load transfer when the tank car ruptured.

The accident at Waverly caused widespread concern about the dangers posed by damaged, loaded tank cars. Wreck-clearing crews, emergency response personnel, and the general public may still be in danger even after the initial derailment because hazardous materials are in the damaged containers.

After investigating several derailments involving a large number of hazardous materials being transported by rail, the Safety Board issued the following recommendations on August 30, 1978, to the Association of American Railroads:

> Complete development and documentation of safety procedures for identifying and assessing hazardous materials dangers, and for coordinating wreckage-clearing operations with local public safety officials. (I-78-14)
>
> Disseminate these safety procedures, as soon as they are documented, to railroad personnel, wreckage-clearing contractor personnel, special emergency response team personnel, and public safety officials in the communities through which railroads operate. (I-78-15)
>
> Establish a procedure for regular reviews of selected railroad wreckage-clearing operations so that these safety procedures can be upgraded promptly as new safety concerns are identified. (I-78-16)

After investigating a derailment at Crestview, Florida, on April 18, 1979, 5/ the Safety Board issued the following recommendation to the Federal Railroad Administration:

3/ Railroad Accident Investigation, Report No. 3838, Interstate Commerce Commission.
4/ Railroad Accident Report--"Derailment of Louisville & Nashville Railroad Company's Train No. 584 and Subsequent Rupture of Tank Car Containing Liquefied Petroleum Gas, Waverly, Tennessee, February 22, 1978" (NTSB-RAR-79-1).
5/ Railroad Accident Report--"Louisville and Nashville Railroad Company Freight Train Derailment and Puncture of Hazardous Materials Tank Cars, Crestview, Florida, April 8, 1979" (NTSB-RAR-79-11).

> Analyze risks to wreck-clearing personnel during wreck-clearing operations involving hazardous materials releases to determine needed health safeguards, operating precautions, and medical treatment capabilities for hazardous materials exposures, and establish appropriate safety requirements based on its findings. (I-79-13)

The Association of American Railroads (AAR) responded positively to recommendations I-78-14 through -16 on February 22, 1980. The Federal Railroad Association (FRA) responded to recommendation I-79-13 by contracting for a study of wreckage-clearing procedures which is scheduled to be completed in March 1981. All four recommendations are now in an open status pending joint action by the FRA and the AAR.

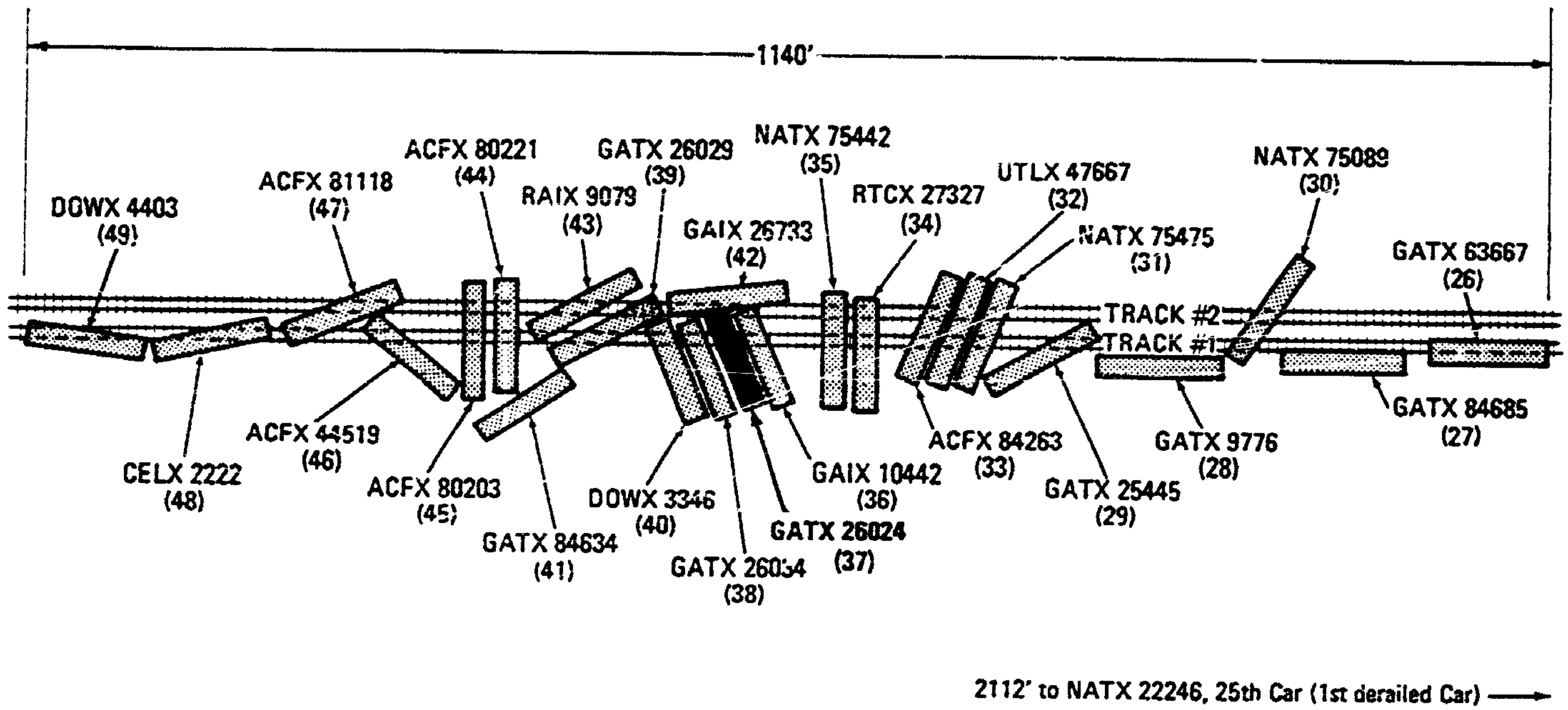
During its investigation of a derailment near Inwood, Indiana, on November 8, 1979, Safety Board investigators again observed the unknown dangers being faced by wreck-clearing personnel as damaged hazardous materials tank cars were being handled. These risks are being studied, but no guidelines, procedures, or requirements have been published to help wreck-clearing personnel assess these dangers. Therefore, this special investigation was initiated to determine what action could be taken to reduce these risks.

GATX 26024, a damaged, but unruptured, DOT Specification 112 tank car, was made available for examination and testing after its derailment at Inwood, Indiana. Documentation of the type and severity of damage to GATX 26024, as well as testing of the residual strength of the structure after the accident, should contribute to the formulation of guidelines for handling damaged tank cars at derailment sites, as well as contributing to the body of knowledge concerning the structural integrity of damaged tank cars. Additionally, this special investigation of tank car GATX 26024 employed a methodology which could be used as a guide for any future testing that may be conducted on the structural integrity of tank cars.

Cooperating with the Safety Board as parties to this special investigation were the FRA, the AAR, the Compressed Gas Association, Hulcher Emergency Services, and the General American Transportation Corporation. Members of the investigative group included experts in fracture mechanics, tank car design, compressed gas shipments, and hazardous materials.

DERAILMENT AND PRODUCT HANDLING

About 5:45, e.s.t., on November 8, 1979, cars 25 through 49 of Conrail freight train IHEN-8 derailed 1 mile east of Inwood, Indiana. The train consisted of 3 locomotive units, 90 cars (76 loaded and 13 empty), and a caboose. Twenty-four of the 25 derailed cars contained hazardous materials. The shipments included: one acetic anhydride, one butyl cellosolve, one butyl methacrylate, six ethyl acrylate, two ethyl chloride, two ethylene oxide, one isobutyl alcohol, one methacrylic acid, one propylene naphtha, one propylene oxide, one sodium hydroxide, and five vinyl chloride. Eight of the derailed hazardous materials cars released some product. (See figure 1.) The Safety Board conducted a field investigation of this accident.



NOTE: Numbers in parenthesis show location of Car in Train.

Figure 1.--Plan view of accident site.

Tank car GATX 26024 was the 37th car in the train and was the 12th car to derail. The tank car contained 183,400 pounds of vinyl chloride, a highly volatile, extremely flammable gas. Vinyl chloride is a colorless, sweet-smelling product, and its vapors irritate the eyes; it becomes explosive when mixed with air. Tank car GATX 26024 came to rest completely inverted with the manway dome and associated valves buried so that they could not be examined.

A severe dent, caused by a similar tank car striking the tank, was evident from the center to one end. The volume reduction caused by the dent was estimated onsite at 1,000 gallons, or about 4 percent of the car's total volume. The only information available from the freight waybill was the weight of the product in the car and the volume of the tank car shell. Using this information, the volume of product in the tank was assumed to be less than the 87 percent maximum permitted by 49 CFR 173.314. The wreck-clearing crew concluded that the damage had not reduced the vapor space (outage) in the tank to a dangerous level.

After a preliminary inspection, the car was left undisturbed and virtually unattended until a similar car arrived for load transfer. On the third day after the accident, a similar car was brought in and a mound of earth was prepared alongside GATX 26024 so that it would be level and properly supported after righting. The tank car was righted by attaching cables around both ends of the car and at the manway dome. As much of the lifting force as possible was applied to the undamaged end of the car. It was necessary to right the car to gain access to the valves and appurtenances located in the dome of the tank car.

Internal pressure was checked as soon as access was gained to the valves in the manway dome. The pressure, 27 psi, was considered to be low and thus, it was safe to proceed. The car lading was transferred immediately after righting, and GATX 26024 was loaded onto a flat car and sent to General American's repair facility at Hearne, Texas. (See figure 2.)

METHODOLOGY FOR TESTING GATX 26024

Tank car GATX 26024 was manufactured in March 1975, according to DOT specification 112 S340W. The car was of stub sill design 5/ and had a coupled length of 53 feet. The tank was 47 feet long and 10 feet in diameter and had a capacity of 26,090 gallons. The tank was constructed of 5/8-inch AAR TC-128 grade "B" steel, which had a minimum tensile strength of 81,000 pounds per square inch. The steel plates were joined by machine-welded butt joints, and the tank was certified to contain a pressure of 340 pounds per square inch. The tank was equipped with a Midland A-3480 safety valve with a start-to-discharge pressure of 280.5 pounds per square inch and a flow capacity of 36,640 cubic feet per minute. The car was equipped with head shields and shelf couplers.

5/ A stub size tank car has draft sills at each end for mounting couplers and utilizes the tank as part of the car's draft sill structure.

Figure 2.--GATX 26024 after derailment and before testing.

A three-phase test plan was developed for use as a guide for the investigation of the structural strength of GATX 26024. The major actions to be accomplished in each phase were —

- o Phase A:
  (1) Thoroughly document the significant damage to the tank structure.
  (2) Conduct nondestructive testing of critical damage areas.
  (3) Estimate burst pressure of tank.

- o Phase B:
  (1) Pressure test the tank car to determine residual tank strength.
  (2) Record data on changes in deformation of tank during the pressure test.
  (3) Pressure test the relief valve.

- o Phase C:
  (1) Determine areas from which metallurgical coupons 6/ should be taken.
  (2) Metallurgically examine critical areas and the rupture site.

Appendix A contains a copy of the preliminary plan for testing GATX 26024

Phase A

(1) Tank Structure Damage.—The damaged area was on the left side of the car and extended from the weld at the middle of the tank toward one end. The damage included the head-to-tank weld and the tank head.

The damage to the tank was observed and thoroughly documented. The first step was to draw a 1- by 1-foot grid on the damaged area of the tank. The origin of the grid was the top of the tank halfway along its length. Longitudinal stations were established at 1-foot intervals toward the tank's "B" end. The last regular longitudinal station was at 20 feet, followed by 20 feet 11 inches (tank-head-weld), 21 feet 5 inches, and 21 feet 10 inches. Circumferential stations were established at 1-foot intervals around the tank surface.

A 1/2-inch diameter steel rod was formed into a semicircle and tack welded onto the tank at station 20 feet 11 inches. This reestablished the contour of the tank head. To establish the geometry of the dented surface, a cord was stretched horizontally from this rod successively at each circumferential station forward toward the undamaged end of the tank, giving the approximate location of the undeformed tank surface at each longitudinal station. This methodology for measuring the volume of the dent could be used at accident sites to assist the wreck-clearing crews in their decisionmaking process.

6/ Samples of material cut from the test vehicle to be examined for metallurgical properties.

Based on the measurements taken from an established line representing the original tank contour and the cardboard radii templates used to determine the bend radii, computer calculations indicated that the decrease in the interior volume of the tank was approximately 1,092 gallons, or 4.2 percent of interior volume. (See figures 3 and 4, and appendix B.)

(2) Nondestructive Testing of the Damage Area.--Dye penetrant and portable magnaflux nondestructive inspection techniques were used on the inside and outside damage areas to determine whether cracking had occurred as a result of the derailment damage. Sharp bend radii, especially at the tank head to cylinder weld, were considered critical damage areas. (See figure 5.) Wheel burn areas or gouges with associated cold working would have been suspect, but were not present. No cracks were found by the inspection.

(3) Estimations of Tank Burst Pressure.--Before the tank was pressure tested, the eight representatives of the parties to the investigation were asked to predict the pressure at which the dent would start to deflect outward and also the pressure at which the tank would rupture. The predictions on deflection ranged from 75 to 290 psi, with five parties predicting ranges between 120 and 197.5 psi. None of the parties expected the tank to rupture during the pressure test which was to be limited to 340 psi proof pressure.

Phase B

(1) Residual Strength of Tank Car.--The tank was filled with water at 80° F, and an air pressure powered water pump was attached. A cord was stretched longitudinally at circumference station No. 12 from the steel circular rod at the tank-to-head weld to a damaged bracket forward of the midtank weld. Two lightweight indicators were taped to the tank at stations 11.5 and 16 and placed on the stretched cord. A mark was made on each indicator to denote the initial location of the tank shell, and as pressure was applied, it was possible to determine when and how much the dent deflected outward. The dent began deflecting at 40 psi.

(2) Changes in Tank Deformation During Pressure Test.--After 24 minutes of operation, the pump was shutdown because it was not pumping sufficient volume at the low pressures. At this point, water main pressure of 75 to 80 psi was used to continue the test. About 47 minutes after the start of the test, the pressure was reduced to 0 psi, and permanent deformation of the tank shell was noted. Subsequently, line pressure was reapplied for 1 hour 23 minutes and the dent continued to deflect and more nearly assume the original tank contour. After 2 hours 52 minutes, a large portion of the dent had been displaced outward to approximately the original shape, the pump was started, and the internal pressure was increased. After 3 hours 19 minutes, the tank ruptured at 205 psi. The pressure decreased immediately, and no propagation of the rupture was noted. The tank ruptured in the weld between the left side of the saddle plate and the tank, near the stub sill reinforcing plate. (See figure 6.) Dent dimensions were recorded using the same method used before pressurization. (See appendix B.)

26,000 Gallon Capacity – Non Insulated
DOT – 112S340W
For Vinyl Chloride Service

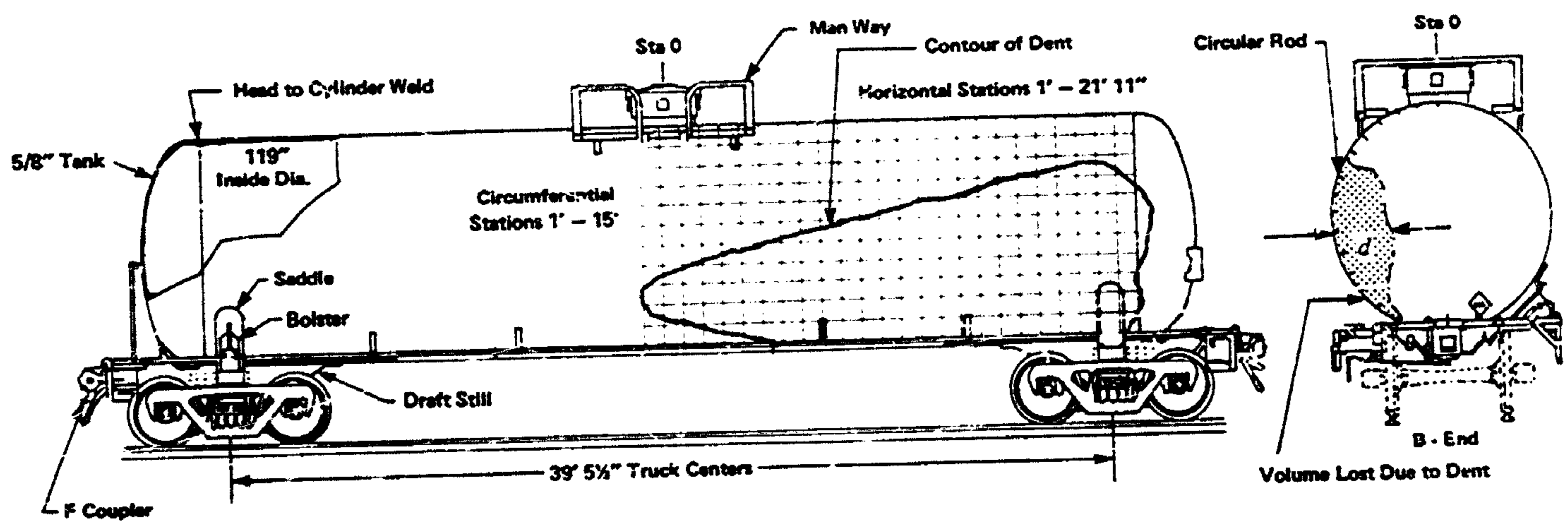
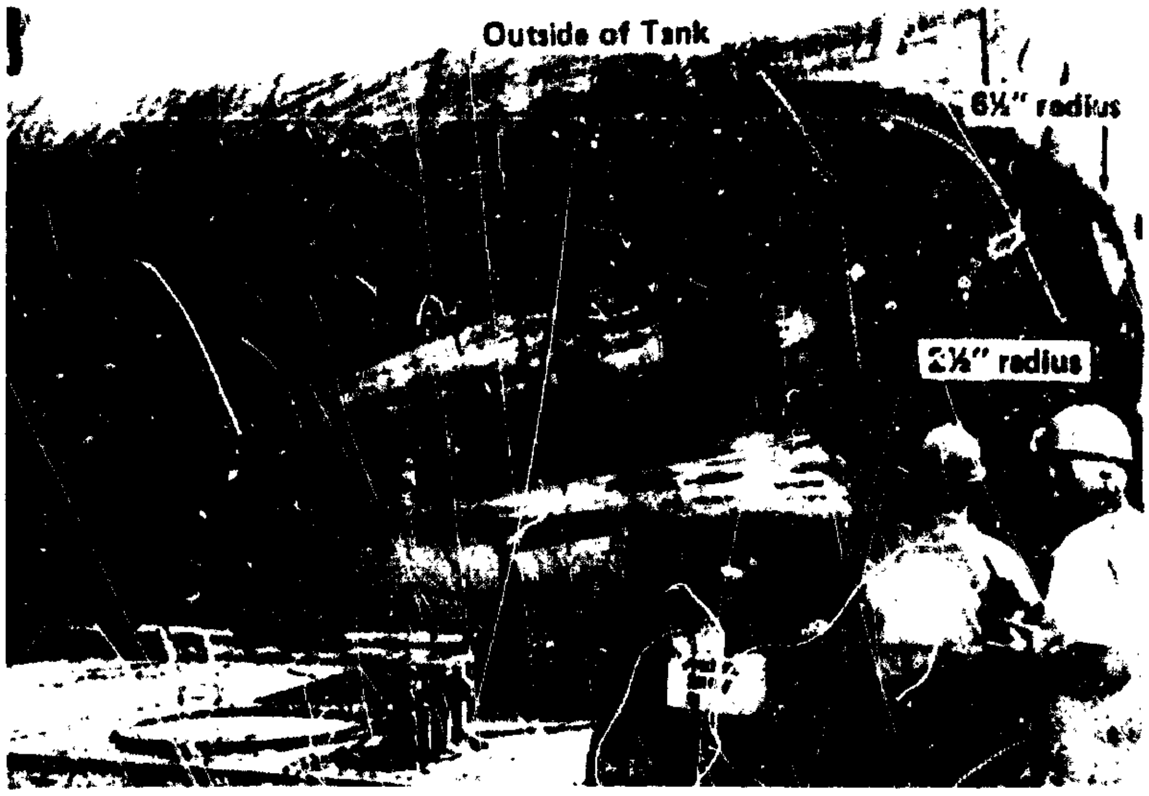


Figure 3.—Tank car nomenclature and measurement scheme.



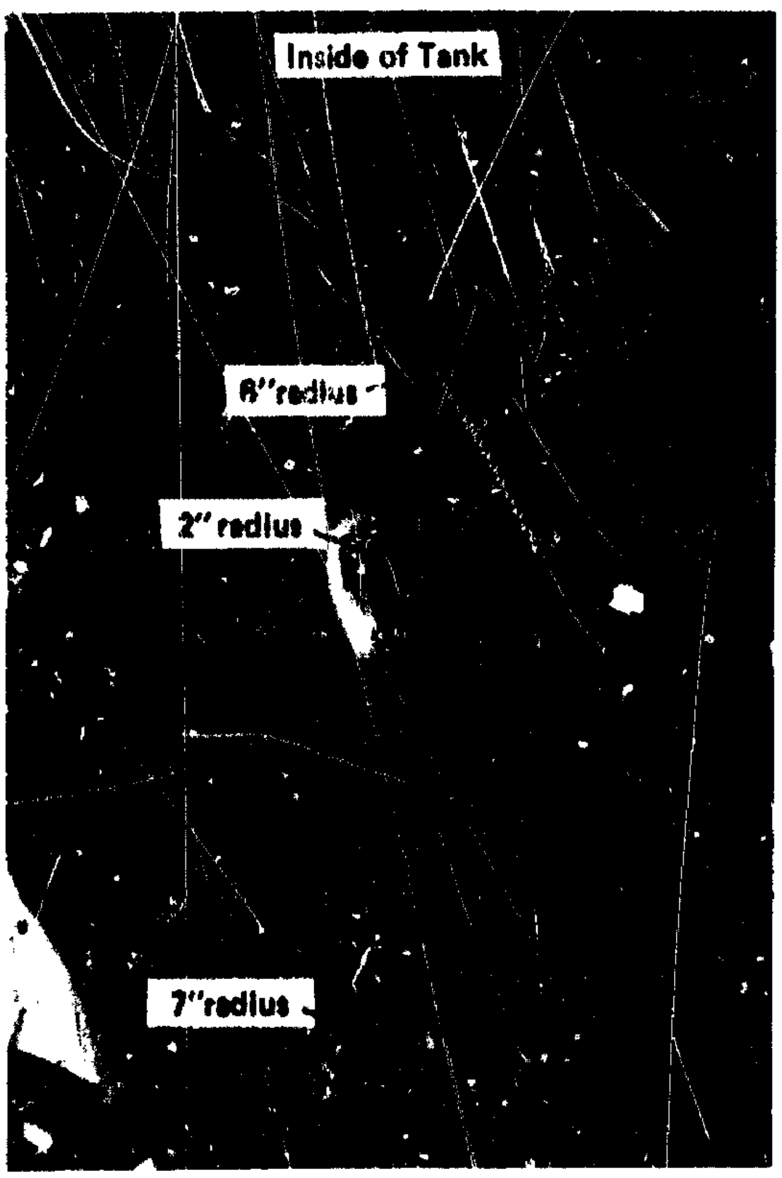


Figure 4.--Dent bend radii before pressure testing.

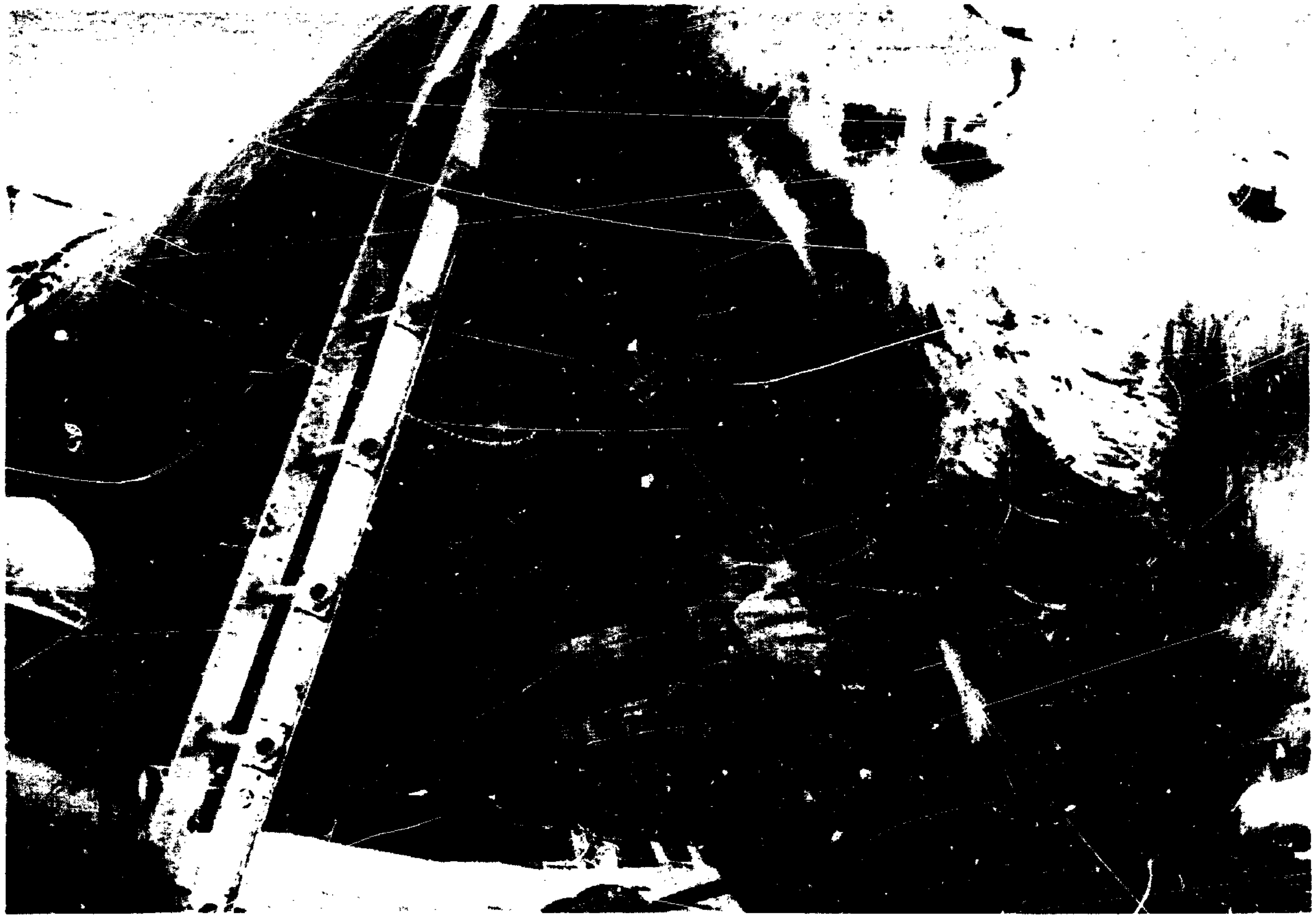


Figure 5.--End view of GATX 26024 showing circular rod used to establish original tank contour.

Figure 6.--Side view of GATX 26024 showing rupture of tank.

(3) Relief Valve Pressure Test.--The A3480 pressure relief valve (Serial No. CL 293), which was on the tank at the time of the derailment, was manufactured by Midland Manufacturing Co., Skokie, Illinois. When it was pressure tested, it started to discharge at 280 psi, which was consistent with the rated start-to-discharge pressure of 280.5 psi.

Phase C

(1) Metallurgical Coupon Areas.--Metallurgical testing was conducted on the lower left end of the tank at the draft sill reinforcing plate; lower left end of the tank at the bolster reinforcing plate and the bolster saddle plate; lower right end of the tank at the bolster reinforcing plate and the bolster saddle plate; middle section of the tank head at the maximum bend of the tank head; upper section of the tank-to-head weld at maximum radius bends; and middle right side of the tank (out of the damage area.) (See figure 7.)

(2) Metallurgical Examination of Critical Areas and the Rupture Site

Tank Car Head - (Normalized Steel Plate 3)

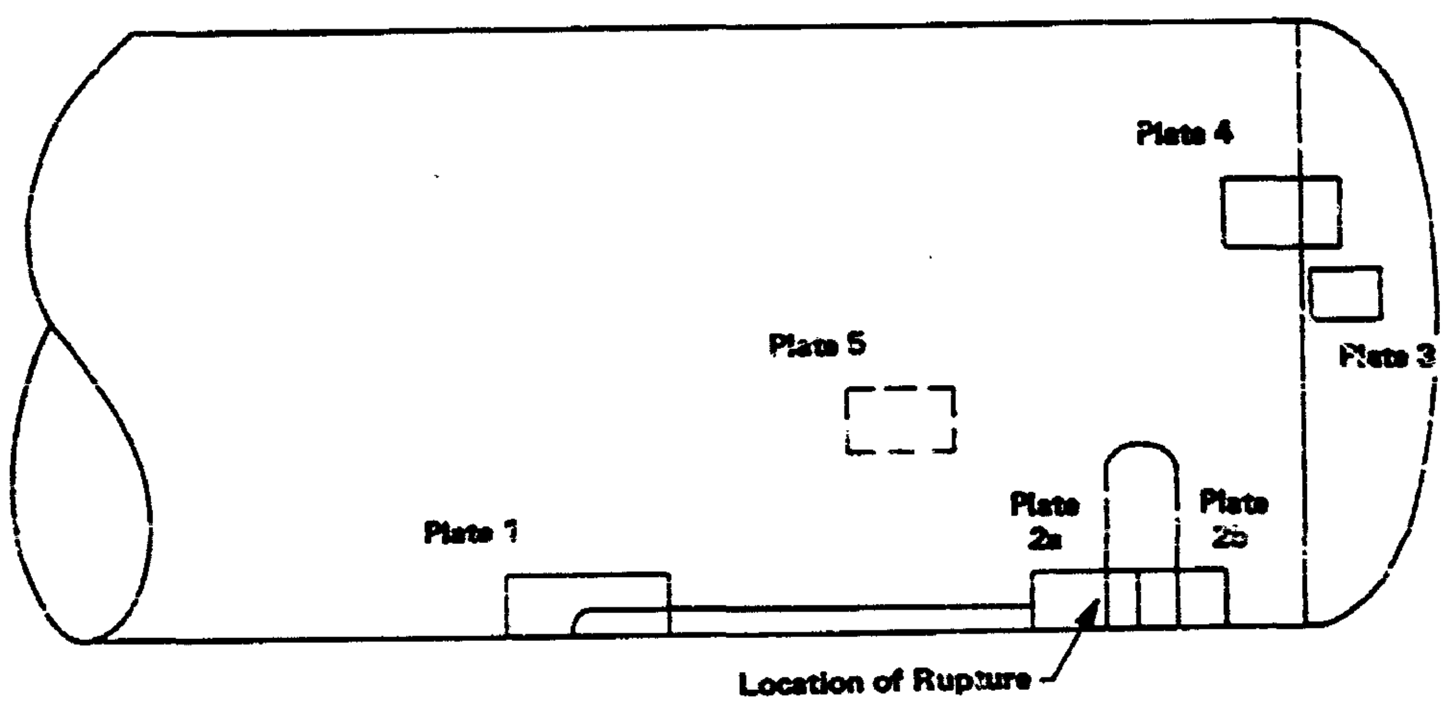
A sample was taken from the area of minimum radius of curvature and maximum apparent strain to determine the role of deformation caused by the accident damage on the structural capacity of the steel. The metallurgical examination revealed that; (1) the hardness of the metal in the bend area was slightly higher than the hardness of the metal in the undeformed area; (2) the hardness of the metal in the deformed area was higher than the hardness of the metal near the center of the specimen; (3) the fracture surfaces showed fully ductile fractures 7/ in both the deformed and undeformed regions; and (4) the impact energy levels for the undeformed area were significantly higher than the deformed area.

See appendix C, a study entitled "Report of the Metallurgical Examination of Test Coupons from GATX 26024" which was commissioned by the FRA. The Safety Board concurs with the findings.

Fracture Area - Plate 2A (Nonnormalized Steel)

The fracture extended from the heat-affected zone (HAZ) 8/ of the fillet weld to the tank base metal in the immediate vicinity of the bolster structural support. The combination of reduced toughness (as indicated by increased hardness in the HAZ) and the formation of a "hinge" at the bolster structural support caused the tank to fail at this point. The tank fracture was a completely ductile failure. (See figure 8 and appendix C.)

7/ Failure of metal resulting from being stretched or drawn thin, the failure occurs because of a sliding action of the internal particles over one another.
8/ That portion of the base metal which was not melted but whose mechanical melted properties and microstructure have been altered by welding.



Coupon No.	Location (See Appendix B)		Purpose
	Circumfer.	Horizontal	Determine
1	14 - 15	11 - 12	Weld strains, effectiveness of stress relief
2a	13 - 14	19 - 20.5	Failure analysis
2b	14 - 15	19 - 20.5	If cracked in weld & bend radius
3	9 - 10	21 - 22	If cracked in worst head bend radius
4	7 - 8	20 - 21	If cracked in worst bend in weld
5	opposite side		Physical properties, unstrained

Figure 7.--Metallurgy sample locations.

Figure 8.—Cross section of rupture showing origin of crack in the heat affected zone of the attachment weld.

Other Tank Specimens - (Plates 1, 2A, 2B, 4, and 5)

An examination for physical properties revealed that the steel in the tank shell met or exceeded the requirements for TC 128 grade "B" steel. The tank structure showed a significant increase in hardness in the HAZ, or the welded areas. The test specimens showed 25 percent brittle fracture at room temperature and 85 percent brittle fracture 9/ at 0° C. (See appendix C.)

TEST RESULTS

Tank car GATX 26024 was examined in an effort to determine the safety margin in handling and unloading a severely damaged tank car at an accident site. The investigators and onscene persons had been concerned about the size of the dent and apprehensive about physically righting the car, as well as transferring its product. However, the pressure test revealed that the internal pressure of 27 psi at the accident site left a considerable safety margin since the tank did not fail until it reached 205 psi. This was still below the 340 psi pressure to which the tank was originally tested.

The size of the dent was of concern because it significantly reduced the volume of the container. Vapor space was needed to provide additional volume should the liquid expand because of heat. The service crew that emptied the tank at the accident site estimated that the volume loss in the tank was 1,000 gallons — the calculated volume loss was 1,092 gallons. Although the accident site estimate of dent volume was reasonably accurate, a problem developed at the accident site in determining the actual volume of product in the tank. Such determinations from product weight can be difficult, and there is a need to quickly provide accident site personnel with volume information on damaged tank cars so that they may make intelligent assessments of the existing hazards.

The failure pressures of the tank and the potential failure area were not accurately predicted by the investigation group. The tank actually ruptured at a pressure 40 percent below the minimum estimated failure pressure, and the failure originated at an unexpected location. It should also be pointed out, however, that the estimates were made using only visual examination. Although magna flux and dye penetrant would normally be available in the field, they are not always used. Of course, in the case of a loaded car, no inside testing could be done. The fact that experts had difficulty estimating failure modes and pressures, demonstrates that adequate safety guidelines do not currently exist. The accident history of tank car ruptures 10/ at accident sites establishes a need for such guidelines.

9/ The failure of metal resulting from abrupt separation of the internal particles from one another without any sliding action between the particles.

10/ Railroad Accident Report—"Derailment of Louisville & Nashville Railroad Company's Train No. 584 and Subsequent Rupture of Tank Car Containing Liquefied Petroleum Gas, Waverly, Tennessee, February 22, 1978" (NTSB-RAR-79-1) and Railroad Accident Report—"Louisville and Nashville Railroad Company Freight Train Derailment and Puncture of Hazardous Materials Tank Cars, Crestview, Florida, April 8, 1979" (NTSB-RAR-79-11).

The tank structure demonstrated a notable ability to withstand impact and damage. GATX 26024 exhibited a 40 percent loss of ability to contain product under pressure. The actual failure occurred at a weld between the tank and the damaged supporting structure connecting the tank to the truck and wheel assembly. This failure suggests that the method of attachment of the tank to the stub sill requires further examination.

Other Commodities

GATX 26024, containing vinyl chloride, gave an adequate safety margin for handling and unloading at the accident site. The tests determined that a temperature of approximately 185° F would have to be reached before the pressure inside the tank would have reached the rupture pressure of 205 psi. The rupture pressure of other materials varied. Anhydrous ammonia would have reached rupture pressure at 106° F, and liquefied petroleum gas (LPG) could have reached rupture pressure at 99°. (See table 1.) Such temperatures are possible during the summer months in the United States, and in a fire situation, such temperatures can be easily reached. At Waverly, Tennessee, the damaged tank car ruptured because an existing crack propagated due to an increase in internal pressure, which had been caused by a rise in temperature.

Table 1.--Temperatures at which commodities which are authorized to be loaded in tank cars would reach rupture pressure in the damaged GATX 26024.

Commodity	Temperature (°F)
Chlorodifluoromethane	104
Liquefied Petroleum Gas	99 - 113
Anhydrous Ammonia	106
Chlorotrifluoromethane	138
Dichlorodifluoromethane	140
Methyl Chloride	148
Monomethyl Amine	170
Octafluorocyclobutane	185
Vinyl Chloride (Monomer)	185
Butadiene	200
Butane	210
1,2-Dichlorotetrafluoroethane	215
Trimethylamine	220

Metallurgy Tests

The shell material in GATX 26024 had the ability to withstand 25 to 30 percent strain in areas away from weld and small surface cracks. Testing of welded areas with small surface cracks (0.05 to 0.1 inch in depth) indicated susceptibility to failure at about 5 percent strain, or about the strain associated with a 6-inch radius bend. Such small surface cracks may be detectable under laboratory conditions, but it is unlikely that this type of flaw could be located under derailment site conditions.

The nonnormalized tank steel 11/ plate appeared to be near the static transition temperature for ductile to brittle fracture at normal operating temperatures. The tests indicated that the temperature at the time of the accident could have controlled the actual fracture condition. During the dynamic fracture tests, partial brittle fractures did occur. It is noteworthy that the normalized steel 12/ in the tank car head exhibited no brittle fracture in the dynamic fracture tests, indicating greater toughness for normalized steel structures.

Significance of Test

Damaged tank cars containing hazardous materials at accident sites have been identified as a significant hazard. The current method of using knowledgeable, experienced experts to make estimates about the structural strength of damaged cars that determines subsequent handling of such tank cars has produced disastrous results. The fact that the tank started to deflect at 40 psi and ruptured at 205 psi when the average estimates for these pressures were 100 psi and 340 psi, respectively, indicates that there is currently no accurate method of predicting incipient tank failures. The substantial overestimates of the rupture pressures by experts during this investigation shows the need for a better method of estimating the structural integrity of damaged tank cars.

The tests conducted on GATX 26024 established that testing of damaged tank cars can provide information that could lead to the establishment of guidelines for use by wreck clearing crews who are confronted with the safe handling of damaged tank cars. While one test cannot be used as a criterion for establishing such guidelines, rupture tests of a representative sample of damaged tank cars should provide enough data to accomplish this.

The testing of GATX 26024 also indicated the need to address the problem of estimating the quantity of a commodity actually loaded in a tank car. Most waybills show the commodity weight, but conversion of weight to volume under field conditions can be difficult and result in delays or unsafe estimates if improperly done. The Safety Board believes that shippers should include volume and temperature at the time of loading on shipping papers so that mistakes in field calculations can be avoided.

Another area of concern is the welded attachments to the tank. The attachments are needed to make the tank into a vehicle. Since the failure of GATX 26024 occurred as the result of an attachment weld, this indicates that derailment damages to tank attachments need further examination. Further testing of damaged tanks may identify other areas which may require remedial actions.

11/ Steel which is in an "as rolled" condition or is used in the condition in which it came from the rolling mill.
12/ Steel which has been heated to remove the stresses put into it by the rolling process.

CONCLUSIONS

1. No accurate method for estimating the residual strength of damaged railroad tank cars at derailment sites currently exists.

2. The method now used for determining the structural integrity of damaged tank cars during wreck-clearing operations has been emperically derived and can lead to underestimation of the dangers present.

3. The existing body of knowledge on damaged tank cars does not produce accurate predictions on the behavior of such cars in a postderailment environment.

4. The tests conducted during this investigation show that it is possible to develop better guidelines for estimating the structural integrity of damaged tank cars based on new information acquired through a rupture testing program.

5. Nondestructive testing methods, in this instance, did not reveal any cracks in the tank although cracks in the tank or attachment welds would affect the pressure at which a damaged tank would rupture.

6. The normalized tank car steel in the tank head has less propensity for brittle fracture than the nonnormalized steel in the tank body.

7. Small surface cracks in the heat affected zone of welds can develop into ruptures if the damaged tank shell contour is changed by increases in internal pressure.

8. If the freight waybill included the number of gallons loaded in a tank car and the loading temperature, the information would assist emergency crews at a derailment site in more accurately determining the volume of the commodity in the tank.

RECOMMENDATIONS

As a result of the findings and conclusions of this special investigation, the National Transportation Safety Board made the following recommendations:

-- to the Research and Special Programs Administration of the U.S. Department of Transportation:

> Amend 49 CFR 174.25 to include a requirement that the volume, in gallons, and the temperature at which the pressurized liquefied gases were loaded in tank cars be entered on bills of lading, waybills, and shipping orders. (Class II, Priority Action) (I-80-1)

-- to the Federal Railroad Administration:

> Develop guidelines for handling tank cars containing pressurized liquefied gases at accident sites based on research and tests of a representative sample of damaged tank cars. (Class II, Priority Action) (I-80-2)

— to the Association of American Railroads:

> Examine ruptured tank cars to determine what effect current design and welding practices for welded tank attachments may have on the structural integrity of tank car loaded with pressurized liquefied gases in the derailment environment, and report the resultant findings. (Class II, Priority Action) (I-80-3)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD:

/s/ JAMES B. KING
Chairman

/s/ FRANCIS H. McADAMS
Member

/s/ PATRICIA A. GOLDMAN
Member

/s/ G. H. PATRICK BURSLEY
Member

ELWOOD T. DRIVER, Vice Chairman, did not participate.

October 15, 1980

APPENDIXES

APPENDIX A

PRELIMINARY TEST PLAN FOR EXAMINING THE STRUCTURAL INTEGRITY OF GATX 26024

BACKGROUND

In the aftermath of a train derailment it is necessary for emergency service personnel to be involved in the handling of tank cars loaded with hazardous materials. Often these cars have had varying degrees of structural damage which can make their handling dangerous. It is important that an assessment of the damage to each car be made to determine its condition in order to devise the safest procedure for handling the car. Assessment of the critical condition of a tank car would be expedited if criteria were available for "sizing up" the structure. This test plan has been developed for the purpose of investigating ways and means of damage assessment through systematic testing of a damaged tank car and to determine the feasibility of the procedure.

PURPOSE OF THE TEST

The purpose of the investigation is to document the extent and nature of the damage to the car and determine its residual structural strength. Ultimately, it is hoped to determine the feasibility of developing criteria with which emergency and salvage personnel can assess the risk of operating around or moving a damaged tank car which contains hazardous materials.

TEST ARTICLE

GATX-26024, a tank car, type DOT 112S340W, containing flammable compressed vinyl chloride gas was car No. 37 of a 91 car train which derailed near Inwood, Indiana, on November 8, 1979. The car was built and last tested in 1975, and has a capacity of 26,090 gallons or 187,000 pounds and a light weight of 72,000 pounds. It had an extremely severe dent on the lower left side. It has been cleaned and is at the Hearne, Texas Repair Shop.

TEST PLAN

A three phase plan is outlined to accomplish the purpose of the project. Phase A describes the external documentation of damage and failure prediction. Phase B outlines a test which may cause the tank to rupture. Phase C outlines the inspection and testing of major damage area samples.

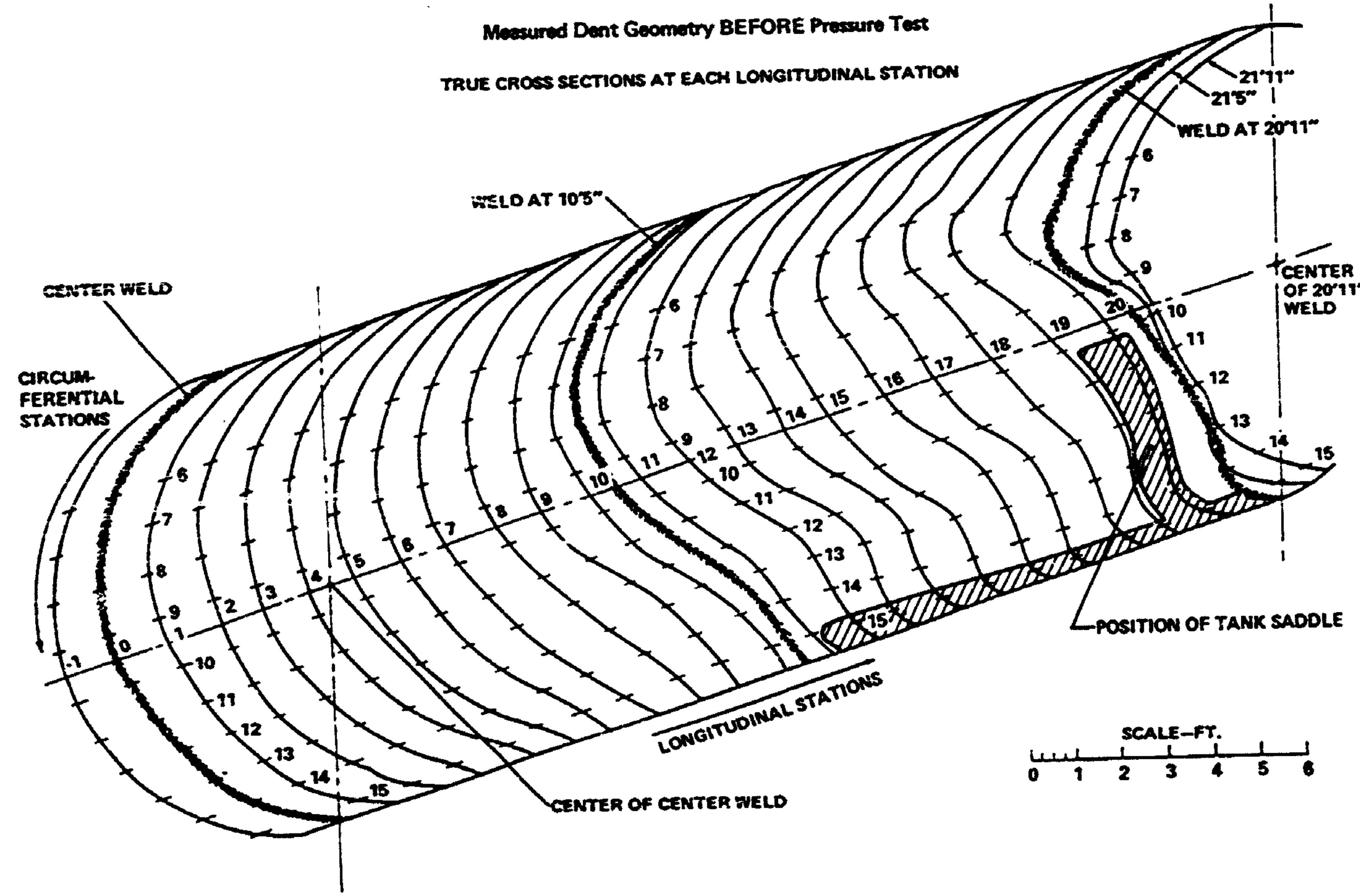
PHASE A - This phase of the test will be conducted at the Hearne, Texas Repair Shop of the General American Transportation Corporation.

A thorough documentation of the tank structure damage is to be accomplished. The measurements of dents and scrapes and description are to be recorded in a group report. Data such as length, width, depth, and bend radii of dents are required. Photographs are to be taken to give a pictorial record of the damage. Nondestructive tests (NDT) such as dye penetrant inspection are to be accomplished to determine the extent of external cracking. It should be kept in mind that only those methods of NDT which are practical for accident conditions should be used. The truck and bolster condition should be documented as well since a misalignment of the assembly could cause overload of the tank when the car is righted and set on the trucks.

PHASE B - Pressure testing is proposed which will determine the validity of the predictions given in Phase A. Standard hydrostatic methods are to be used with at least 90 percent of the tank capacity filled with water. The test pressure is to be applied up to 340 psi. With a capacity of 26,090 gallons, 23,500 gallons of water would be used. The safety relief valve will be modified to allow the higher pressure to be applied. Since the tank car is to be repaired, pressure in excess of 340 psi will not be applied. Any changes in damage to the tank as a result of this test are to be documented. Photographs of the test damage are to be taken.

PHASE C - In the final phase, appropriate coupons will be cut from the major damage area and inspected in a metallurgy laboratory. During the derailment, cracks may have been initiated in the damage area. The purpose of the metallurgical testing is to determine the length of the initial crack at the origin. A determination of the type of fracture is to be made at the initial and the propagated crack. Also, whether the fracture is propagating shear or tearing shear.

APPENDIX B
DENT GEOMETRY DATA

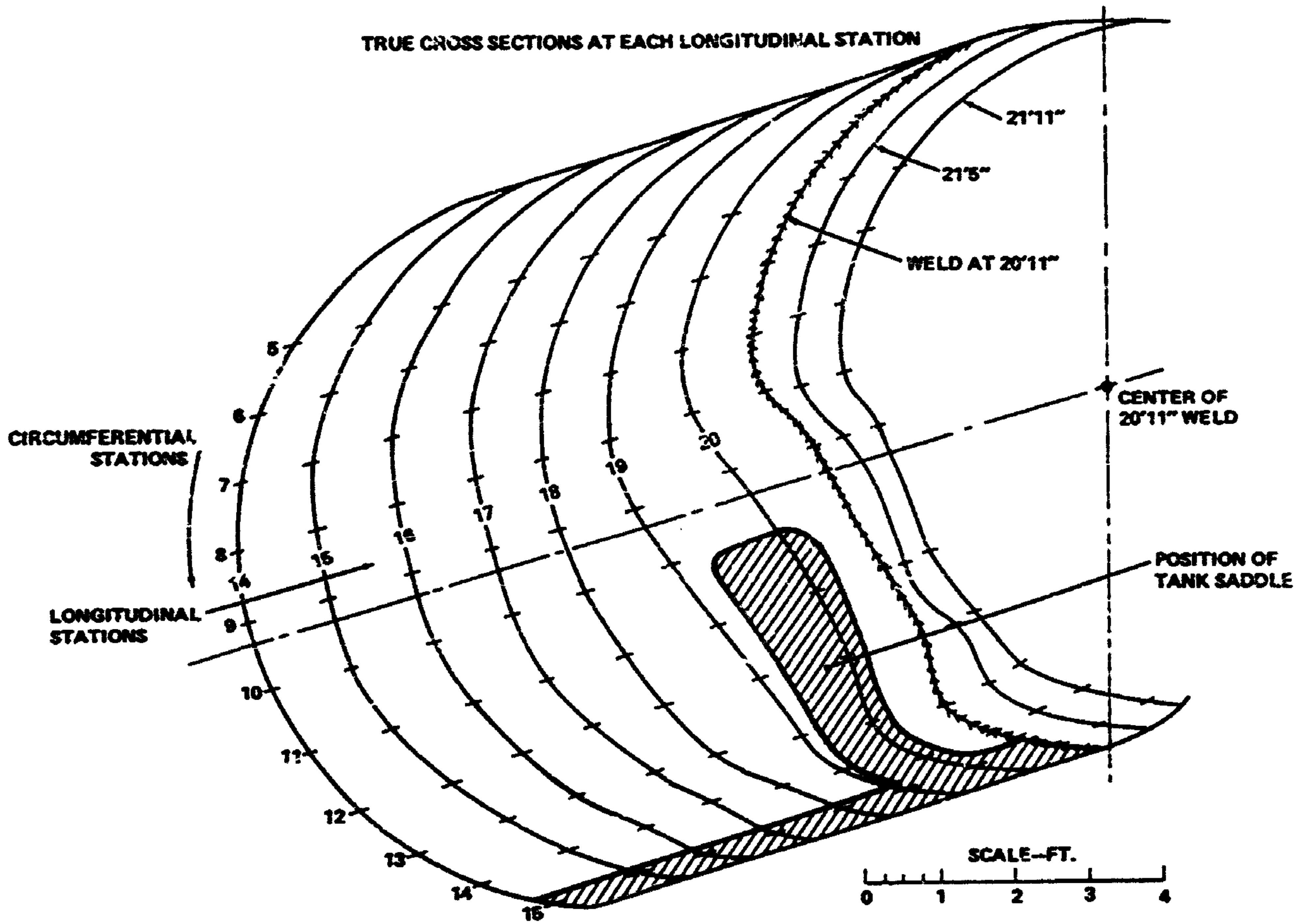


Dent Geometry Data

Longitudinal Station - (ft. from center weld)	Circumferential Station - (ft. from top center line)								
	7	8	9	10	11	12	13	14	15
0		0	¼	3/4	1	1	3/4	½	0
1		½	3/4	1¼	1½	1 3/4	1 3/4	1¼	0
2		3/4	1¼	2	2	2 3/4	3	2½	1
3		3/4	1 3/4	2	3	4	4	3	2
4		1	2	2½	4½	5½	4 3/4	3 3/4	3
5		1¼	2	3½	5½	6	5½	4½	4
6		1	2¼	4½	6½	7	6 3/4	6	5
7		1	3	5½	8	9½	9½	8½	6
8	¼	1	3 3/4	6½	10	12½	13	11 3/4	9½
9	1	1¼	5¼	8	12	15½	16 3/4	14	9½
10	1	1½	6½	9½	15 3/4	18	19	14½	8
11	1½	2½	7 3/4	11	15½	19½	20½	13 3/4	7½
12	1½	3½	9	12½	17	21¼	21	13¼	6½
13	1½	4½	10	13½	19	22 3/4	21	12½	6
14	1	5½	11	14½	19½	23½	20 3/4	12	6
15	1	6 3/4	12	15 3/4	20½	24	20½	11¼	6
16	3/4	8 3/4	13¼	16 3/4	21½	25	20½	10 3/4	4
17	½	9¼	15½	18¼	22	25	19½	9½	1½
18	0	11	17	20½	22½	24½	18	7½	0
19	0	12½	18 3/4	23½	25	23½	16½	5½	0
20	0	10¼	18 3/4	23	23½	19½	12	2½	0
20'11"	0	7½	16½	20	20	18	9	1½	0
21'5"	0	4	14	16½	15	15	7	1½	0
21'11"	0	0	11	12½	12	11	5	1½	0

Note: Depth measurements are in inches and are taken from a line which represents the original surface of the tank.

Measured Dent Geometry AFTER Pressure Test



DENT GEOMETRY DATA - AFTER PRESSURE TEST

Circumferential Station (ft.)	Longitudinal Station (ft.)								
	15	16	17	18	19	20	20'11"	21'5"	21'11"
8	1 1/2	1 1/4	1	1/2	0	1 1/2	2 1/4	2	0
9	1 3/4	1 3/4	1 1/2	1 1/2	3	8 1/2	10 1/2	9 1/2	9
10	0	1	1 1/2	2 1/2	6	13	13	12	11
11	0	3/4	1	2 1/2	7 1/2	13	13	10 1/2	9 1/2
12	2	3	2 1/2	2	7	10	12	11	8 1/2
13	2 1/4	2 3/16	2 1/2	1/2	3 1/2	4	4 1/2	4 1/2	3 1/2
14	2 1/2	3	2 1/2	1	0	0	0	0	0

APPENDIX C

REPORT OF METALLURGICAL EXAMINATION OF TEST COUPONS FROM CATX 26024 BY ARTHUR D. LITTLE, INC.

SUMMARY OF METALLURGICAL TESTS ON MATERIALS
FROM DAMAGED TANK CAR
CATX 26024

1. Introduction

A 100-ton railroad tank car was involved in an accident and received a severe dent but did not rupture. The car was a pressure tank car to DOT Specification 112S 340W loaded with Vinyl Chloride. The car was subsequently subjected to a pressure test and ruptured at 205 psi.

A series of metallurgical tests and inspections have been carried out on the six test plates cut from the pressure tank of this car. The principal objectives of the test program were to analyze the pressure test rupture, and to determine the properties of the tank steel and how these were altered by the accident distortion.

The materials and practices used in manufacture were to the relevant standard in the AAR Specifications for Tank Cars and DOT regulations.

The pressure tank is manufactured from 5/8-inch thick TC128 steel. It comprises two semi-elliptic heads 10-ft diameter, and four cylindrical rings each rolled from one piece of steel, butt welded to form a 42-ft long cylinder. The bulk of the accident damage occurred in the "B" end head and the adjacent fourth ring. The material for the tank heads is required to be normalized, but that for the tank cylinder is not.

Prior measurements and tests on the damaged pressure tank are described in the body of this report. Dye penetrant and portable magnaflux tests made at the points of minimum bend radius in the tank head and at the tank head to cylinder butt weld revealed no cracking. During the pressure test, the dent was progressively blown out at 70-90 psi, leaving a smaller dent in the region of reinforcing provided by the tank cradle.

Little further change occurred up to 205 psi, at which point the tank ruptured at the cradle/cylinder fillet weld. Plate 2A containing the rupture was one of those selected for analysis.

2. Tests on the Tank Head in the Region of Maximum Apparent Strain (Plate 3)

The region of maximum apparent strain, i.e. the minimum radius bend, occurred in the tank car head. The tank car head steel is normalized as is required in the AAR Specs. Plate 3, which contains this bend, was examined to determine the influence of prior deformation on material performance (strength). This bend radius subsequent to the accident was estimated to be two inches and it increased to approximately four inches upon repressurization. Various methods were employed to assess possible loss in toughness. These procedures included Charpy tests and J_{1c} ductile fracture tests.

In general, an increase in hardness correlates with a decrease in ductility and toughness. Hardness measurements were performed away from the bend region to obtain a value which characterizes the material and at the bend cross section using the standard Rockwell B scale. The results are given in Table 1. Knoop* hardness measurements (100 gram weight) taken across the bend cross section to assess local changes in hardness in the bend region and the further increase near the surface of this cross section (subjected to higher deformation). These results indicate that the material toughness in the region of the bend is likely to be reduced below that of the remainder of the plate.

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* Knoop hardness measurements involve use of an excessively light load enabling higher local resolution but yielding less reliable results.

Table 1

Plate 3 - Head--Region of Maximum Bend Hardness Data

	Rockwell B	Knoop
Center of Cross Section	88	230
Near Surface of Cross Section		242
Away from Deformed Region	82	

Charpy specimens[(1)*] were cut from both the deformed and undeformed regions of Plate 3 and subjected to the standard impact tests at room temperature. The fracture surfaces of Charpy specimens cut from the deformed and undeformed regions showed fully ductile fracture. Yet, the Charpy impact energy levels for the undeformed and deformed material specimens were 98 and 42 ft-lbs, respectively, indicating significant prior deformation influence.

Limited quasi-static testing using precracked Charpy type specimens has been performed to further identify the loss of toughness indicated by dynamic Charpy results. The Charpy type specimens used were side grooved to create plane strain, flat fracture as recommended by Ritchie et al.[(2)] The J_{1c} ductile fracture initiation parameter was estimated from the load deflection record. An estimate of J following substantial crack growth was made using the same formula to enable a prediction of the Tearing Modulus (T), a parameter used to compare resistance to ductile tearing (J_{1c} is only applicable to the initiation of fracture from a pre-existing crack).

The quasi-static precracked Charpy tests were performed on three samples which were cut from the deformed section of Plate 3. The specimen was oriented tangentially with respect to the bend, with the notch oriented radially. The fracture specimens showed completely ductile fracture surfaces (no cleavage) with substantial laminar tearing.

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* References are given at the end of this report.

A substantial variance in both J_{1c} and T was found. This may be the result of laminar tearing and local deviations of the crack direction to the rolling direction of the plate. Lesser variation was recorded in the corresponding Charpy impact values which are associated with the energy to break the specimen rather than to initiate a fracture. The fracture surface created in the impact tests is large compared to that created in the J_{1c} tests and thus, likely to show less variation from specimen to specimen.

Further testing would be required to accurately estimate J_{1c}, T and their variances. It already can be observed from the limited testing that the material has a large resistance to quasi-static tearing. Calculations based on elastic-plastic fracture mechanics concepts, which are discussed in detail later, predict that a 0.01-inch pre-existing crack would be needed to initiate fracture at the region of maximum bend in Plate 3.

Note that the maximum strain level in Plate 3 was approximately 25%, which is within the requirements of the AAR Specifications. Thus, it is not surprising that no failure occurred.

3. <u>Tests on Tank Cylinder Material (Plates 1, 2A, 2B, 4 and 5)</u>

The tank cylinder material is not normalized steel. Plate 5 is used as the standard since it was not damaged in the accident. Tensile specimens cut in the rolling direction from Plate 5 give a yield stress of 64 ksi (0.2% offset) an engineering ultimate stress of 98 ksi and a 32% elongation in two inches.

Hardness measurements were taken in the reference Plate 5 and in Plates 2A and 4. Plate 2A contains the crack that caused the tank to fail during the pressure test. This crack originated in the heat affected zone of a fillet weld, as is discussed in more detail subsequently.

Therefore, hardness measurements were taken away from the crack, near the crack, and in the heat affected zone from which the crack grew. Plate 4 contains a major butt weld between tank cylinder and tank head. Hardness measurements were taken as an indication of possible loss in toughness in the heat affected zone of this weld. The results are given in Table 2.

Table 2

	Rockwell B	Knoop
Plate 5	88	
Plate 2A - Away from Crack	88	
Plate 2A - Near Crack	92	284
Plate 2A - Heat Affected Zone		342
Plate 4 - Base Material		265
Plate 4 - Heat Affected Zone Butt Weld		307

Note a slight increase in RB hardness in Plate 2A near the crack and a significant increase in KHN in the heat affected zone. A similar increase in KHN in the heat affected zone of the butt weld (Plate 4) is also observed.

Charpy specimens were taken from Plate 2A in the base material away from the welded and cracked regions and impact tests were performed at room temperature and 0°C. The Charpy impact energies determined are 107 ft-lbs and 77 ft-lbs at room temperature and 0°C, respectively. The room temperature specimens exhibited approximately 25% cleavage on their fracture surfaces, and the 0°C specimens had substantial (75%) cleavage fracture. These results indicate that the dynamic toughness is in the transition region and that the upper shelf dynamic toughness (ductile) must begin above room temperature. The static toughness transition generally occurs at a somewhat lower temperature. Thus, the room temperature static toughness is likely to be fully ductile. The fracture surfaces of the Charpy impact specimens exhibited macro laminar tearing, an indication of a weak plane (the rolling direction) in the material.

Plate 2B was chosen for examination because it contained a similar fillet weld to that in Plate 2A and possible cracking was expected. Careful examination did not reveal any transverse cracking.

Plate 1 also contained a fillet weld and was examined for possible cracks. No cracks were found.

4. Examination of the Fracture

The crack which developed during repressurization and caused the tank to fail is contained in Plate 2A. The crack originated on the outer tank surface in the heat affected zone of the fillet weld and grew through the tank wall. The interior surface of the tank shows significant permanent deformation surrounding the crack, which indicates that the fracture involved high energy, low velocity tearing.

Both fractography (the direct observation of the fracture surface) and a metallographic section transverse to the fracture in a partially fractured area were used to characterize the fracture (see photograph in body of report). To examine the fracture surface directly, a portion of the fracture which had penetrated completely through the thickness of the plate was cut out. This fracture was then examined by ADL using a low power optical microscope and then given to Professor Pelloux at MIT, an expert on fractography, for his examination. The cross-section of the partially cracked region from an area adjacent to the through crack was examined with a metallurgical microscope in the unetched and etched condition. In addition, both microhardness (Knoop) and macrohardness (Rockwell B) were taken on this section.

From our observation of the fracture surface and as confirmed by Professor Pelloux using the Scanning Electron Microscope, the fracture was ductile with no indication of cleavage anywhere on the surface. There was extensive microlaminar tearing parallel to the surface of the steel as the crack propagated.

Examination of the cross section containing the crack revealed the origin of the crack in the heat affected zone of the fillet weld and confirmed that the propagation was ductile. As the crack propagated, ductile tearing occurred with void formation and laminar tearing. Void formation is apparent near the tip of the crack.

A portion of the fillet weld attaching the cradle plate to the tank cylinder had given way and the through wall fracture originated near the end of this fillet weld tear. The local stress state at this location of fracture initiation was greater than the nominal value as a result of both the change in stiffness due to the saddle plate and the stress concentration at the termination of the fillet weld tear. The combination of reduced toughness in the heat affected zone (measured here as increased hardness) and the stress concentration at this location resulted in reduced ductility and crack growth.

A theoretical estimate of the conditions for ductile fracture from the fillet weld heat affected zone was made. It was assumed that the crack has grown through the less tough, heat affected zone, and a prediction made of the stress/strain level needed to cause this crack to propagate through the base metal. The prediction is based on the J_{1c} fracture criterion. Thus, it is necessary to be able to estimate "J" as a function of stress level in the section. To accomplish this, the uniaxial material response was modelled as bilinear with σ_{ys} = 64 ksi, σ_{ult} = 124 ksi (true stress). The elongation at failure is approximately 32%. This data was developed from Plate 5. The following dimensions were used: specimen thickness w = 0.62 inch and crack depth a = 0.08

inch. For such surface cracks, the stress intensity factor K [$J = (1-\nu^2) K^2/F$] can be approximated by the formula[3].

$$K = \sigma\sqrt{\pi a}\ F(a/w)$$

$$F(x) = \sqrt{\frac{2}{\pi x} \tan \frac{\pi x}{2}} \left[\frac{0.923 + 0.199\ (1-\sin \frac{\pi}{2} X)^4}{\cos \frac{\pi}{2} X} \right]$$

This formula is based on elastic analysis. Plastic effects can be accounted for in an approximate manner by increasing the crack length by an amount $r_p = \frac{1}{\sigma\pi} (\frac{K}{\sigma ys})^2$. This is known as the Irwin crack length correction.

The elastic prediction for K_1 at applied stress equal to the yield stress is

$$K_1 = 36(10)^3 \text{ ksi } \sqrt{in}$$

and the crack length correction is $r_p = 0.016$ inch yielding a corrected stress intensity of $K_1 = 39(10)^3$ psi $\sqrt{in}$ and in a corresponding J value of 47 lb/in.

On the other hand, we can approximate J in the fully plastic range by $J \approx a\pi\epsilon\sigma$, where ϵ is the strain level and σ is the stress level as seen by the edge crack of depth a. This formula is a variation of that developed by Shih and Hutchinson [4] for shallow edge cracks (small a/w). Predictions for J as a function of strain/stress level as calculated from this plasticity formula are reported in Table 3.

Table 3

J Integral as Function of Stress/Strain Level

Stress σ_{ys}(ksi)	Strain ϵ (%)	J in-lb/in^2
64	0.002	33
66	0.011	182
68	0.021	363
70	0.032	580
72	0.043	795
76	0.064	1260
80	0.085	1770

The J integral vs. stress estimates developed here can be used in conjunction with data on the fracture initiation value of J (J_{1c}) to predict the stress/strain state which can cause crack growth to initiate. Charpy data for the undeformed plate material at room temperature was found to average 107 ft-lbs. This is believed to be on the upper shelf for toughness. The Charpy values can be converted to J_{1c} using approximate formulae from Reference 5, giving

CVN	J_{1c}
107 ft-lbs	1010 in-lb/in^2

A single quasi-static test was successfully performed to verify this J_{1c} estimate. A side grooved and fatigue precracked Charpy specimen cut from Plate 5 was used for this purpose. The J_{1c} testing followed the procedure discussed earlier and recommended by Ritchie[(2)] The resulting J_{1c} value is 1002 in-lb/in^2. (This close agreement with the J_{1c} obtained by conversion of Charpy impact energy may be fortuitous.)

These data suggests that a precracked (a = 0.08 inch depth) portion of the tank car plate will be able to sustain approximately 5 to 6 percent strain prior to fracture initiation.

The same formulae can be used to estimate the flaw size which would lead to fracture initiation in a plate which developed a local radius of curvature of two inches (a 25% strain level), the smallest radius of curvature condition found in the present investigation. The resulting predictions for critical flaw size is a = 0.01 inches. At the strain level associated with the bend test specified for this plate (33%), the critical flaw size is approximately 0.007 inch.

From these results, we can see that the affect of a flaw of 0.08 inch depth (equivalent to the thickness of the heat affected zone of the fillet weld) is to reduce the apparent ductility of the material, and thus the strain level at which fracture will initiate.

5. Conclusions

The principal results obtained from the various tensile and fracture toughness tests and metallographic examinations were:

- The fracture originated in the relatively brittle heat affected zone of the fillet weld joining the tank cradle to the tank cylinder, on the outside surface of the cylinder. Outside the heat affected zone the failure was completely ductile and involved high energy, low velocity tearing. A portion of this fillet weld had given way between the cradle and the cylinder, and the fracture originated at the end of this tear. This would be a point of high stress concentration under internal pressure, possibly leading to crack initiation. Alternatively, the crack may have originated at the time of the original accident.

- Careful examination of all the test plates, including the regions of butt and fillet welds, failed to reveal any other cracks or partial fractures.

- The toughness of the normalized tank head material was measurably reduced by the deformation, at the point of the minimum radius bend. This was indicated by both hardness and Charpy test results. The strain, however, was within that which the material is specified to withstand; thus, cracking would not be expected.

- The material of the tank cylinder is not normalized (unlike the tank head). Fracture toughness test results indicated a risk of dynamic (unstable) cleavage fracture at low ambient temperatures. This risk is particularly present if the tank contains pressurized gas, which will continue to exert force on the pressure tank structure after a leak has occurred.

More tests are recommended both on samples from this tank car and from similar accident damaged vehicles.

REFERENCES

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2. Server, W.L., R.A. Wullaert, and R.O. Ritchie, "On the Use of Side Grooves in Estimating J_{1c} Fracture Toughness with Charpy-Size Specimens," J. Eng. Materials and Technol., Vol. 102, pp 192-199, April 1980.

3. Tada, Stress Analysis of Cracks Handbook, Del Research Corp., 1973.

4. J. of Engineering, Materials and Technol., October 1976.

5. Rolfe, S.T., Barson, J.M., Fracture and Fatigue Control in Structures Application of Fracture Mechanics, Prentice-Hall, 1977.

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